

# The dark matter as a light gravitino (II)<sup>1</sup>

Gilbert MOULTAKA

*Laboratoire de Physique Théorique et Astroparticules  
UMR5207–CNRS, Université Montpellier II  
Place E. Bataillon, F–34095 Montpellier Cedex 5, France*

**Abstract.** We address the question of gravitino dark matter in the context of gauge mediated supersymmetry breaking models.

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## INTRODUCTION

In scenarios where supersymmetry breaking is triggered by non-perturbative dynamics of some (secluded) gauge sector and communicated to the MSSM by a messenger sector through perturbative gauge interactions, the susy breaking scale  $\sqrt{F}$  and the mass scale  $\Lambda$  of the secluded gauge sector can be well below the Planck scale. Recent developments [1] stressing the existence of metastable susy breaking vacua, have renewed the interest in such gauge-mediated susy breaking (GMSB) scenarios opening new possibilities for the model-building [2], and appear to be very interesting from the early Universe point of view as well [3]. On the other hand, the gravitational interactions which play a minor role for susy breaking in GMSB models remain physically relevant through the coupling to supergravity, at least in order to absorb the unphysical goldstino component, to adjust the cosmological constant to a small value and to avoid a massless R-axion. Moreover, if the above mentioned two scales combine to trigger the electroweak symmetry breaking yielding  $G_F^{-1/2} \sim (\alpha/4\pi)kF/\Lambda$ , where  $G_F$  is Fermi's constant (and  $0 < k \leq 1$  measures the secludedness of the secluded sector), then the gravitino mass  $m_{3/2} \simeq F/(\sqrt{3}m_{\text{Pl}}) \sim (4\pi/\alpha)(\Lambda/\sqrt{3}km_{\text{Pl}})G_F^{-1/2}$  where  $m_{\text{Pl}}$  is the reduced Planck mass, is expected to be very small ( $\lesssim \mathcal{O}(1)$  GeV) and is the lightest supersymmetric particle (LSP). The question then arises as to which particle can be a good candidate for the cold dark matter (CDM) in this case? To answer this question requires an unconventional treatment as compared to the Neutralino “vanilla” candidate or even to the heavy gravitino candidate in the context of gravity mediated susy breaking models. Indeed, in contrast with the latter where the hidden sector is typically too heavy to be produced at the end of inflation, the secluded and messenger sectors of GMSB provide stable particles that may be present in

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<sup>1</sup> based on work in collaboration with K. Jedamzik (*LPTA-Montpellier*), M. Lemoine (*IAP-Paris*) [6, 7]; and work in progress, M. Kuroda (*Meiji-Gakuin*), M. Lemoine (*Paris*), M. Capdequi-Peyranère (*Montpellier*).

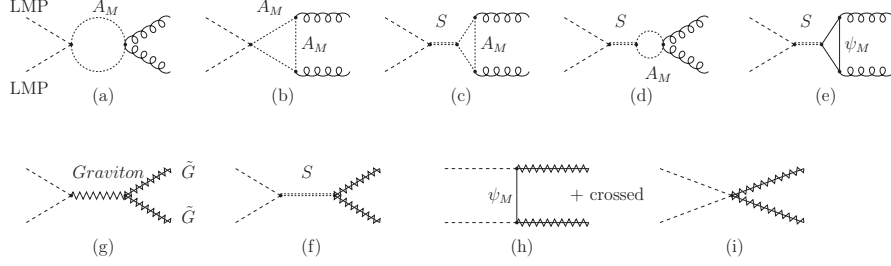
the early Universe for a sufficiently heavy reheat temperature  $T_{RH}$ . We consider hereafter such configurations assuming that only the messenger (including the spurion) sector can be produced and illustrate its relevance to the issue of the CDM.

## A MESSENGER SOLUTION TO THE GRAVITINO PROBLEM

The mass degeneracy within a supermultiplet of messenger fields is lifted by susy breaking leading to a lighter and a heavier scalar messengers with masses  $M_{\pm} = M_X(1 \pm kF/M_X^2)^{1/2}$  and a fermionic partner with mass  $M_X$  (where  $F$  and  $M_X$  are related to the dynamical scale  $\Lambda$ ). Thus  $kF/M_X^2 < 1$ . Moreover, one has to require  $kF/M_X \lesssim 10^5 \text{ GeV}$  to ensure an MSSM spectrum  $\lesssim \mathcal{O}(1) \text{ TeV}$ . One then expects typically  $M_X \gtrsim 10^5 \text{ GeV}$ . In typical GMSB models the lightest messenger particle (LMP) with mass  $M_-$  is stable due to the conservation of a messenger quantum number. If present in the early Universe the messenger particles are thermalized through their gauge interactions with the thermal bath. The corresponding LMP relic density is calculable similarly to that of the Neutralino LSP. However, it turns out to be typically too large to account for the CDM (albeit fine-tuning) even in the most favorable case of the electrically neutral component of a  $\mathbf{5} + \bar{\mathbf{5}}$  representation of  $SU(5)$  where it is found to scale as  $\Omega_M h^2 \simeq 10^5 (M_-/10^3 \text{ TeV})^2$  with the LMP mass [4]. The situation is even worse in the case of  $SO(10)$  where the LMP is an MSSM singlet with a suppressed annihilation cross-section leading to a very large relic density. One possible cure to this messenger overclosure problem, namely to allow the LMP to decay, can actually turn out to be a blessing regarding a solution to the gravitino problem and simultaneously letting the gravitino account for the CDM in the context of GMSB models.<sup>2</sup> The LMP late decay into MSSM particles can release enough entropy to dilute the initial gravitino relic density down to a level which can account for the CDM in the Universe even for very high  $T_{RH}$ , [5, 6, 7]. For this to work, though, the LMP should dominate the Universe energy density before it decays, and should decay after the gravitino has freeze-out from the thermal bath. The necessary condition  $T_d < T_{MD} < T_{3/2}^f$  [where  $T_d, T_{MD}, T_{3/2}^f$  denote respectively the LMP decay and messenger matter domination temperatures, and the gravitino freeze-out temperature] is then determined by the particle properties and annihilation cross-section and decay width of the LMP, delineating the favorable parts of the parameter space. We have studied this scenario in detail for the case of  $SU(5)$  [6] and  $SO(10)$  [7]. In the next section we concentrate on the latter case with one set of messengers transforming as  $\mathbf{16} + \bar{\mathbf{16}}$ .

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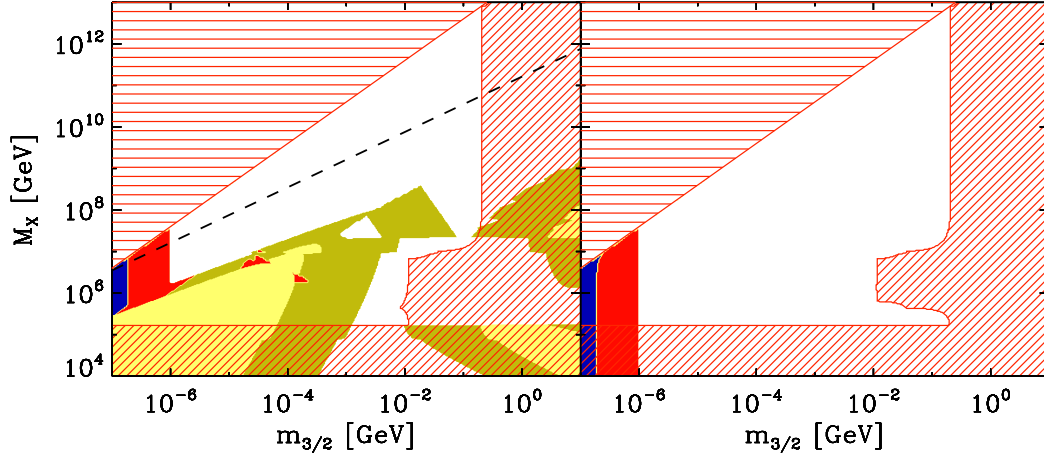
<sup>2</sup> One can easily argue for an unstable LMP once the GMSB model is coupled to supergravity, invoking the violation of the messenger number conservation by gravitational interactions akin to discrete accidental symmetries. The resulting messenger number violating operators are then Planck scale suppressed and would not upset the natural suppression of the flavor changing neutral currents in GMSB models.



**FIGURE 1.** Feynman diagrams of the leading LMP annihilation into 2 gluons (a-e) or 2 gravitinos (f-i).

## GRAVITINO RELIC ABUNDANCE

The entropy release  $\Delta S \equiv S_{\text{after}}/S_{\text{before}}$ , diluting the initial gravitino density, is determined by the temperatures before and after LMP decay and can be approximated to  $T_{MD}/T_d$ .  $T_{MD}$  is given by the LMP yield and mass ( $T_{MD} \simeq (4/3)M_- \times Y_{\text{LMP}}$ ) and  $T_d$  is determined by the LMP width ( $\Gamma_{\text{LMP}} \simeq H(T_d)$ ).  $Y_{\text{LMP}}$  is determined by the LMP annihilation into MSSM particles. Since in our case the LMP is an  $SU(5)$  singlet [4, 7], this annihilation proceeds via loop effects of virtual messengers ( $A_M, \psi_M$ ) and spurion ( $S$ ) exchange, fig.1. We parameterize the thermally averaged leading annihilation cross-section into 2 gluons as  $\langle \sigma_{\text{1loop}} v \rangle \sim f(\alpha_s/4\pi)^2 \kappa^4/s$  where  $\kappa$  is the spurion-messenger coupling ( $W \supset \kappa \hat{S} \mathbf{16}_M \mathbf{\overline{16}}_M$ ),  $\alpha_s$  the strong coupling constant,  $\sqrt{s}$  the C.M. energy and  $f$  a form factor depending on the internal masses. The LMP decay is induced by Planck scale suppressed non-renormalizable messenger number violating operators which can originate from the Kähler potential, e.g.  $K \supset \mathbf{16}_F \mathbf{\overline{16}}_M^\dagger \mathbf{10}_H/m_{\text{Pl}}$ , or from the superpotential, e.g.  $W \supset \mathbf{\overline{16}}_M \mathbf{16}_F \mathbf{16}_F \mathbf{10}_H/m_{\text{Pl}}$ , leading respectively to 2- and 3-body decays, where  $\mathbf{16}_M$  ( $\mathbf{\overline{16}}_M$ ),  $\mathbf{16}_F$  and  $\mathbf{10}_H$  denote respectively the messenger, the standard matter and the electroweak Higgs supermultiplets. We assume a typical decay width  $\Gamma_{\text{LMP}} = (1/16\pi) f' M_X^3/m_{\text{Pl}}^2$  where  $f'$  parameterizes our ignorance of the couplings and possible further phase space suppression. When the necessary temperature conditions are met, the final gravitino relic density is given by  $\Omega_{\text{grav}} = \Omega_{\text{grav}}^{\text{th}}/\Delta S + \Omega_{\text{grav}}^{\text{Mess}} + \Omega_{\text{grav}}^{\text{NLSP}}$  where the last two contributions denote non-thermal production through late decays or scattering. One should also consider various cosmological constraints (hotness/warmness, BBN, species dilution, etc...). In fig.2 we illustrate the case with  $T_{RH} \simeq 10^{12}$  GeV, see also [6]. The horizontal red shading shows the theoretically excluded region where  $k > 1$ ; the other red shading indicates the region excluded by BBN constraints. If the spurion is heavier than the LMP, gravitino cold DM (green region) occurs for relatively light LMPs and  $m_{3/2} \sim 1\text{keV} - 10\text{MeV}$ . More generally, in the models of ref. [8] one finds [7]  $\Omega_{\text{grav}} h^2 \simeq 10^3 f^{0.8} \kappa^{3.2} f'^{1/2} (M_-/10^6 \text{ GeV})^{-0.3} (m_{3/2}/1 \text{ MeV})$  for non-relativistic LMP freeze-out, putting the gravitino relic abundance in the ballpark of WMAP results, for  $\kappa \sim \mathcal{O}(10^{-1})$  and typical ranges for  $f$  and  $f'$ . The LMP can also annihilate into 2 gravitinos through gravitational interactions, fig.1. For very heavy spurions the annihilation cross-section at rest reads  $\langle \sigma v \rangle \simeq (1/24\pi) k^2 M_-^2/(m_{3/2} m_{\text{Pl}})^2$ . It can dominate the 1-loop annihilation, eventually saturating the unitarity limit (the black dashed line in fig.2), thus



**FIGURE 2.** Contours of  $\Omega_{3/2}$  in the plane  $M_X(\equiv M_-) - m_{3/2}$  for one pair of messengers sitting in  $\mathbf{16} + \overline{\mathbf{16}}$  representations of  $SO(10)$ ; the LMP is a singlet under  $SU(3) \times SU(2) \times U(1)$ . We take for illustration  $\kappa^2 \simeq \alpha_s/4\pi$ ,  $f \sim \mathcal{O}(1)$  and  $f' \simeq 5 \cdot 10^{-2}$  and a bino NLSP with  $M_{\text{NLSP}} = 150 \text{ GeV}$ ,  $M_{\text{gluino}} = 1 \text{ TeV}$  and  $kF/M_- \simeq 10^5 \text{ GeV}$ ; blue (hot), red (warm), green (cold) DM with  $0.01 < \Omega_{\text{grav}} < 1$ ; yellow ( $\Omega_{\text{grav}} < 0.01$ ), white ( $\Omega_{\text{grav}} > 1$ ). In the right (left) panel the spurion is lighter (heavier) than the messenger. (taken from [6].)

disfavouring gravitino CDM solutions for a very heavy LMP.

To summarize, a light gravitino can account for CDM irrespective of  $T_{RH}$ , making it a good DM candidate in GMSB: typically if  $T_{RH} \lesssim 10^5 \text{ GeV}$  then the messengers are not produced and thermal gravitinos with  $m_{3/2} \simeq 1 \text{ MeV}$  provide the right CDM density, while for  $T_{RH} \gtrsim 10^5 \text{ GeV}$  the messenger can be present and should be unstable, thus providing a source of entropy production that can reduce a thermally overproduced gravitino to a cosmologically acceptable level. Moreover, various constraints (e.g. on  $T_{RH}$ , [9], or on the gravitino mass [10]) simply do not apply in the scenarios we have illustrated, thus escaping possible tension with thermal leptogenesis.

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